# Structure of chordae tendineae in the left ventricle of the human heart

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ABSTRACT

The bicuspid (mitral) valve complex of the human heart consists of functional units which include the valve leaflets, chordae tendineae and the papillary muscles. The mechanical properties of these functional units depend to a large extent on the link between the muscle and the valve. This link is usually arranged in a branching network of avascular tendinous chordae composed of collagen and elastic fibres, which transmit contractions of the papillary muscle to the valve leaflets. In order to perform their function efficiently, the chordae have to possess a high degree of elasticity, as well as considerable strength and endurance. Human chordae tendineae originating from the left ventricles were obtained from 7 embalmed cadavers and 6 postmortem subjects of various ages. Samples washed in saline were fixed or postfixed in 9% formol saline. Observations were made by illuminating the chordae along their axes. The reflected images originating from the superficial collagenous layers of the relaxed chordae showed a striped pattern 11 μm in width. Scanning electron and light microscopy of the chordae confirmed an undulating pattern of collagen fibrils arranged in bundles of planar waves in register and around the entire circumference of the chorda. The dimensions of the waves correlated with those of the striped reflected pattern. The observed undulating arrangement of the collagen fibrils appears to produce an inherent built-in elasticity which is likely to be of considerable advantage for a tissue which is under continuous repetitive stress. The chordae were covered by endocardium composed of a superficial layer of smooth squamous endothelial cells and an underlying dense layer of elastic fibres. It is suggested that the relaxed striped chordae, consisting of undulating collagen fibrils, straighten when the chordae become stretched by papillary muscle contraction, thereby mitigating the peak stress developed during muscle contraction. On relaxation the elastic tissue tends to return the collagen to its wavy configuration. It is also suggested that the regular wavy pattern of collagen seen in young individuals gradually changes with age by elongation of the wave pattern which eventually becomes randomised. In addition, with increasing age, substantial cushions of connective tissue appear below endocardium while the dense collagenous core has a reduced cross-sectional area which may lead to stretching and eventual rupture of the chordae.

*Key words*: Collagen; elastic fibres; mitral valve.

## INTRODUCTION

The bicuspid (mitral) atrioventricular valve complex of the human heart consists of functional units which include the fibrous trigones, chordae tendineae and papillary muscles (Hall & Julian, 1989; Anderson & Wilcox, 1995). The demanding mechanical conditions reflect on the structure of these components, whose performance depends to a large extent on the strong link between the muscle and the valve. This link, arranged in a branching network of avascular partly innervated chordae is composed of collagen and elastic fibres.

William Harvey (1628), who dissected numerous hearts, commented in his celebrated 'Exercitatio anatomica de motu cordis et sanguinis in animalibus' that the heart's interior resembled an 'accurate and effective apparatus, like ship's rigging, to assist the

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Fig. 1. Mitral valve complex consisting of: valve leaflet (V), chordae tendineae (CT) and anterior papillary muscle (P). ×3.

heart on all sides to produce a fuller, stronger contraction to expel blood from the ventricles'. This early account forms an accurate and picturesque description of cardiac morphology. The arrangement and classification of the chordae including the anatomy of the entire valve complex have been described by Walmsley (1929). Subsequently, Lam et al. (1970) devised a detailed new classification for the mitral valve chordae based on their mode of insertion into the various regions of the valve. Fenoglio et al. (1972) investigated the ultrastructure of canine mitral valves. In this electron microscope study, the cross-sectioned chordae showed layers of endothelial cells on a basal lamina, the underlying layer consisting of collagen with an occasional elastic fibre. Nerve fibres within chordae were observed infrequently. Lymphatics in the chordae originating at the base were reported by Ichikawa et al. (1989). Tucker (1974) used scanning electron microscopy to observe the appearance of the normal features of human chordae from younger subjects. The general conclusion was that branching of the primary chordae occurred by separation of the tendineous part. Lim & Boughner (1976) investigated the morphology and mechanical properties of human mitral valve chordae. Chordae originating from most subjects were reported to have linear arrangement of collagen fibrils, except for 1 specimen from a younger individual which showed undulations. Similar undulations were observed in mouse chordae by Icardo & Colvee (1995). Salisbury et al. (1963) recorded tension in the canine chorda in situ and demonstrated that it varied from the near zero at mid-diastole to a rapidly rising force of 0.7 N at the systolic outflow phase. Hall & Julian (1989) outlined the functional aspects of the combined papillary muscle, chordae and valve system in the left ventricle and suggested that the stimulation of the papillary muscle was likely to be independent of ventricular contractions. They concluded that stretching of the chordae is maximised at the period when the blood is expelled from the ventricle. Anderson & Wilcox (1995) reviewed mitral valve anatomy and described the disposition of chordae in relation to their origin and insertion.

Following related studies on other dense connective tissues (Stolinski, 1995*a*, *b*), inclined light illumination in a reflecting mode, conventional light and scanning electron microscopy were used in the present study to observe the disposition of the structural components of the human chordae tendineae under tension and when relaxed. A permanent and regular planar wave arrangement of collagen fibrils surrounded by 2 distinct layers of elastic fibres and endothelium are present. It is suggested that the described morphology is well adapted to the condition of continuous repetitive stress. These results have partly appeared in abstract form (Stolinski, 1996; Millington-Sanders et al. 1997).

## MATERIALS AND METHODS

Human chordae tendineae originating from hearts judged to be nonpathological were obtained from 7 embalmed and 6 postmortem cadavers (previous consent was obtained). The age of the subjects ranged from 10 to 92 y. The chordae selected for the investigation were mainly of primary type, reaching towards the edge or the rough zone of the valve flaps. Unfixed chordae were placed in cold phosphate buffered saline (PBS) and observed 1 h after removal. Chordae from embalmed cadavers were washed in PBS, postfixed in 10% buffered formol saline and stored. For light reflectance and scanning electron microscopy procedures, the specimens were cleaned in PBS. Fixed or nonfixed chordae were placed on a black background, covered by a coverslip, bathed in PBS and illuminated by a beam of light from a fibreoptic source, at approximately 35° to the plane of the sample. The reflected image was viewed with $\times 4$ and $\times 10$ objectives. Bulk staining with Miller's method (elastic stain) followed by fast green (collagen stain) were used to identify components of the chordae. For conventional light microscopy, chordae fixed in formol saline were dehydrated and embedded in acrylic resin. For scanning electron microscopy, tissues were dehydrated in graded acetone solutions up to absolute and critical point dried. Endothelium was removed from the dried chordae using double-sided tape or a chorda was split to reveal the internal aspects of the collagen fibrils and the elastic fibres. The specimens were subsequently mounted on planchettes and sputter coated with gold.

## RESULTS

The link between papillary muscle and valve leaflet in the human bicuspid atrioventricular valve consists of 8–12 chordae tendineae, 15–20 mm long and approximately 0.45 mm diameter which on approaching the valve leaflet divide into thinner secondary branches (Fig. 1). Relaxed human chordae from younger subjects, when illuminated by an inclined parallel beam of light, displayed distinct 11 μm period striped reflections spanning the entire chorda (Fig. 2*A*). The examined nonfixed specimens of the chordae showed essentially very similar features to those shown in Figure 2*A*. Some chordae from embalmed cadavers appeared to have been fixed under tension and did not display the characteristic stripes. Chordae sectioned tangentially to their surface (Fig. 2*B*) showed collagen fibrils arranged in a planar wave pattern, in register and of a wavelength of similar period to the reflections shown in Figure 2*A*. Figure 3*A* shows 2 distinct dispositions of the elastic fibres. The outer layer (E1) appeared as a network of fibres associated with the endocardium and arranged at inclined angles to the axis of the chorda. The second layer (E2) appeared longitudinally disposed in the lower endocardium and deeper among the wavy collagen. The cross-sectioned chorda (Fig. 3*B*) showed a dense distribution of the elastic fibres within the lower endocardium and a

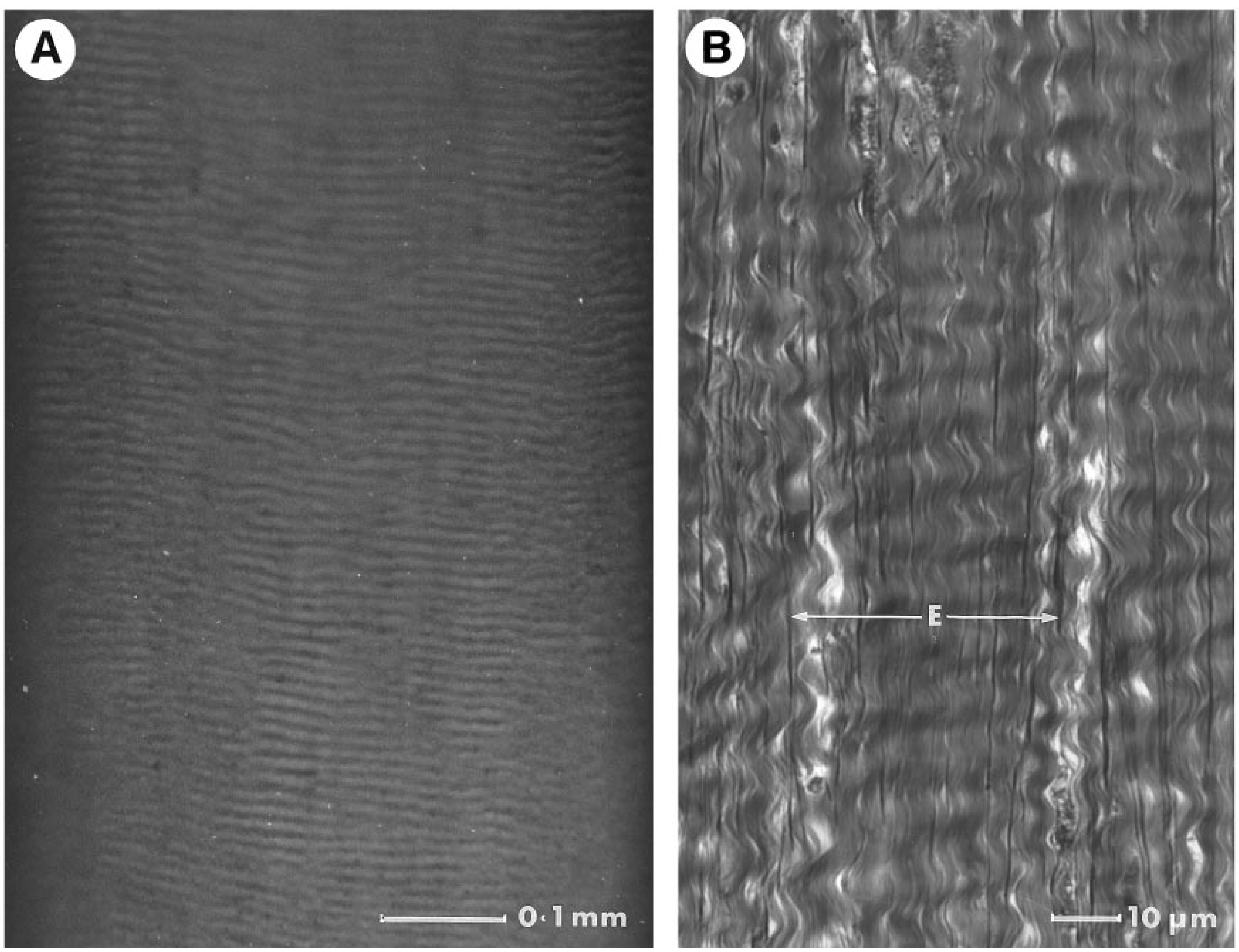


Fig. 2. (*A*) Mitral valve chordae tendineae illuminated along their axis. Striped reflections of 11 μm period, observed from a chorda of a 10 y old human subject. $\times 171$. (*B*) Enlarged fragment of the chorda obtained from the same sample as in *A*, showing a longitudinal section cut parallel and close to the endocardium showing 10 μm period of planar wavy collagen. $\times 946$. E, elastic fibres.

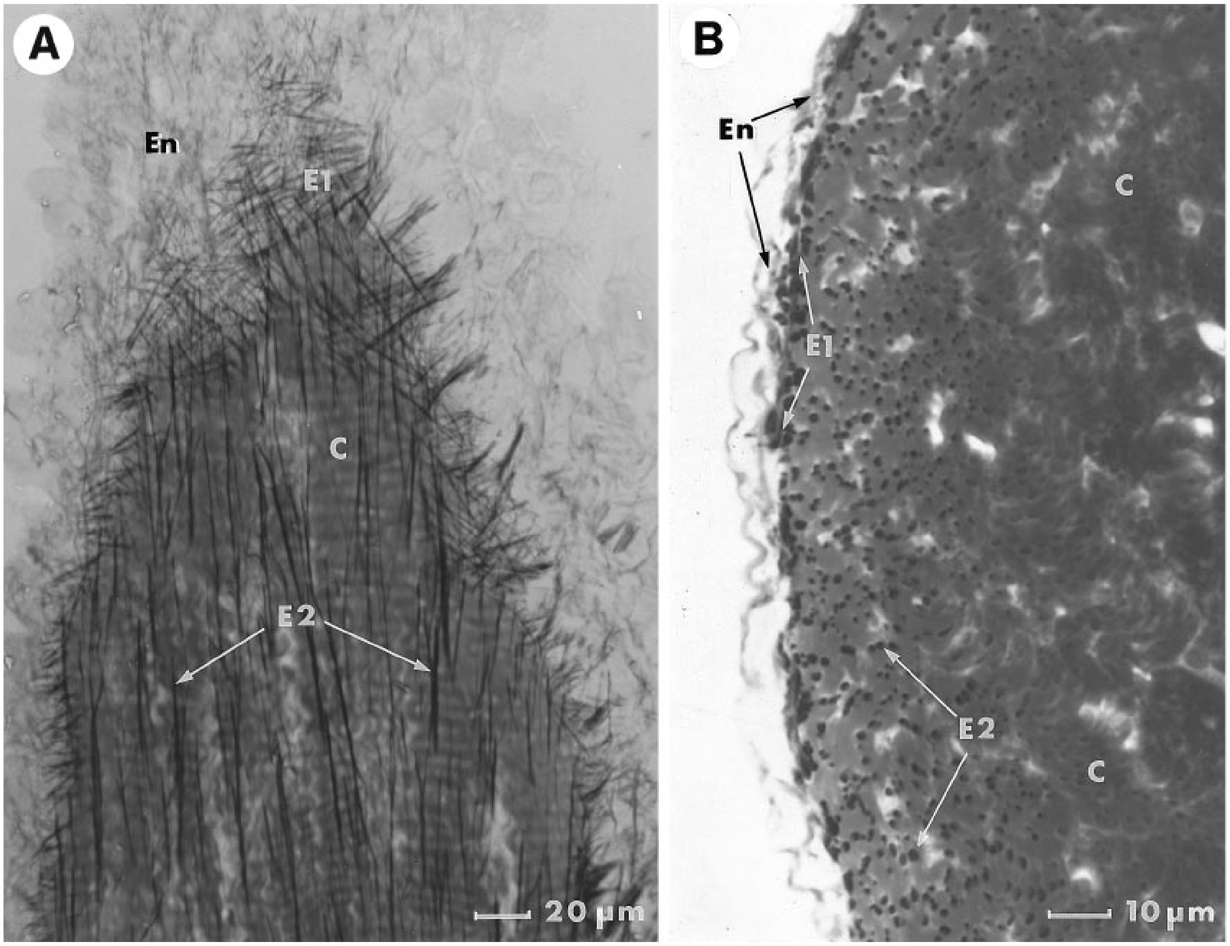


Fig. 3. (*A*) Slightly inclined tangential section of a chorda, showing wavy collagen (C), a network of elastic fibres within the lower endocardium (E1) and the underlying longitudinal elastic fibres (E2). ×340. (*B*) Cross-section of the chorda showing collagen (C) and accumulation of elastic fibres in lower endocardium (E1) and in the deeper regions of the chorda (E2). ×740. En, endothelium.

gradually diminishing number of fibres towards the interior of the chorda. When observed in the scanning electron microscope the exterior of the chorda showed individual endothelial cells (Fig. 4*A*). On removal of the superficial endocardial layer (Fig. 4*B*) a distinct pattern of longitudinally arranged fibres was revealed. The collagenous interior of the chorda (Fig. 4*C*) showed undulating collagen fibrils of similar wavy dimensions to the arrangements shown in Figure 2*B*. The above information, obtained from the presented micrographs, was used to produce a schematic computer drawing (Fig. 5) which illustrates the basic components of the chordae. Chordae from elderly subjects (70–92 y) showed in some subjects characteristic enlargements or cushions of the subendocardial connective tissue (Fig. 6*A*). A mixture of elastic and collagen fibrils tended to be disposed mainly circularly. The disorganised nature of the elastic fibres (Fig. 6*B*) was very noticeable. In some chordae the cross-section of the collagenous core was much smaller than the overall cross-sectional area of the chordae. Observed in a reflecting mode (Fig. 6*C*) some chordae occasionally showed a patch of wavy collagen similar to that in Figure 2*A*, surrounded by fibrils arranged in a broad striped pattern up to 150 μm in width.

## DISCUSSION

Collagen bundles within linearly arranged dense connective tissues frequently show a degree of organisation in the form of specific patterns of the fibres. For example, the collagenous outer layers of the peripheral nerve sheath have been demonstrated to be arranged in planar waves which remain in register around the entire epineurial circumference (Stolinski, 1995*a*). Similarly in the tendons, inclined crimped planes of wavy collagen were observed at intervals along the linearly arranged fibres (Stolinski, 1995*b*). It has been convincingly demonstrated that light reflected from collagen bundles provides a useful guidance to the disposition of collagen fibrils on the surface and the interior of dense connective tissues (Stolinski, 1995*a*, *b*). The striped reflections observed

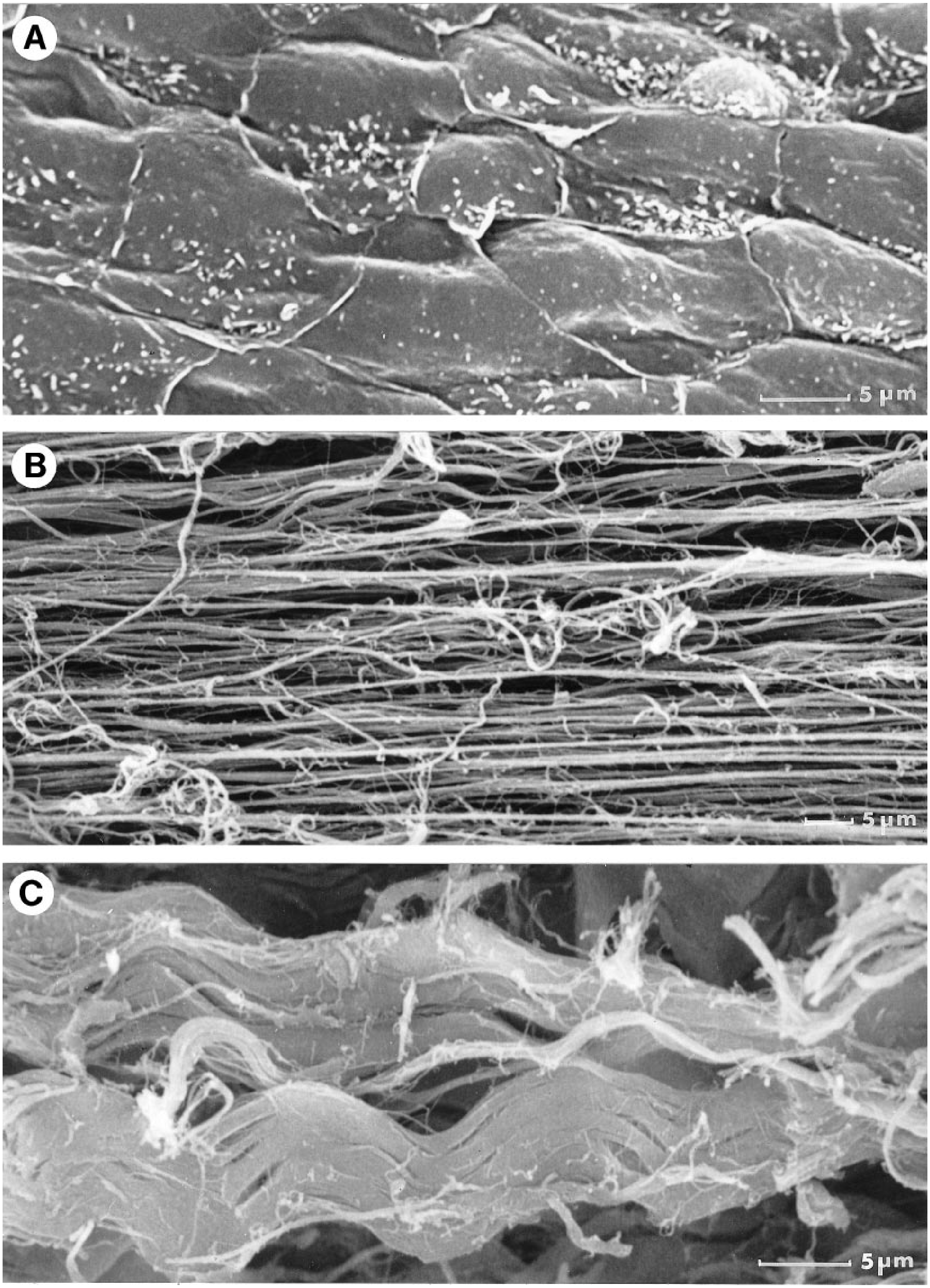


Fig. 4. (*A*) Scanning electron micrograph of external aspect of the endothelial cells of the chorda, obtained from a 23-y-old subject. $\times 3170$. (*B*) The elastic fibres, situated underneath the endocardium which was removed. $\times 1720$. (*C*) Interior of a split chorda. Waves of collagen fibrils with similar dimensions (10.7 µm) to the reflections shown in *A* and undulations in *B*. $\times 3260$.

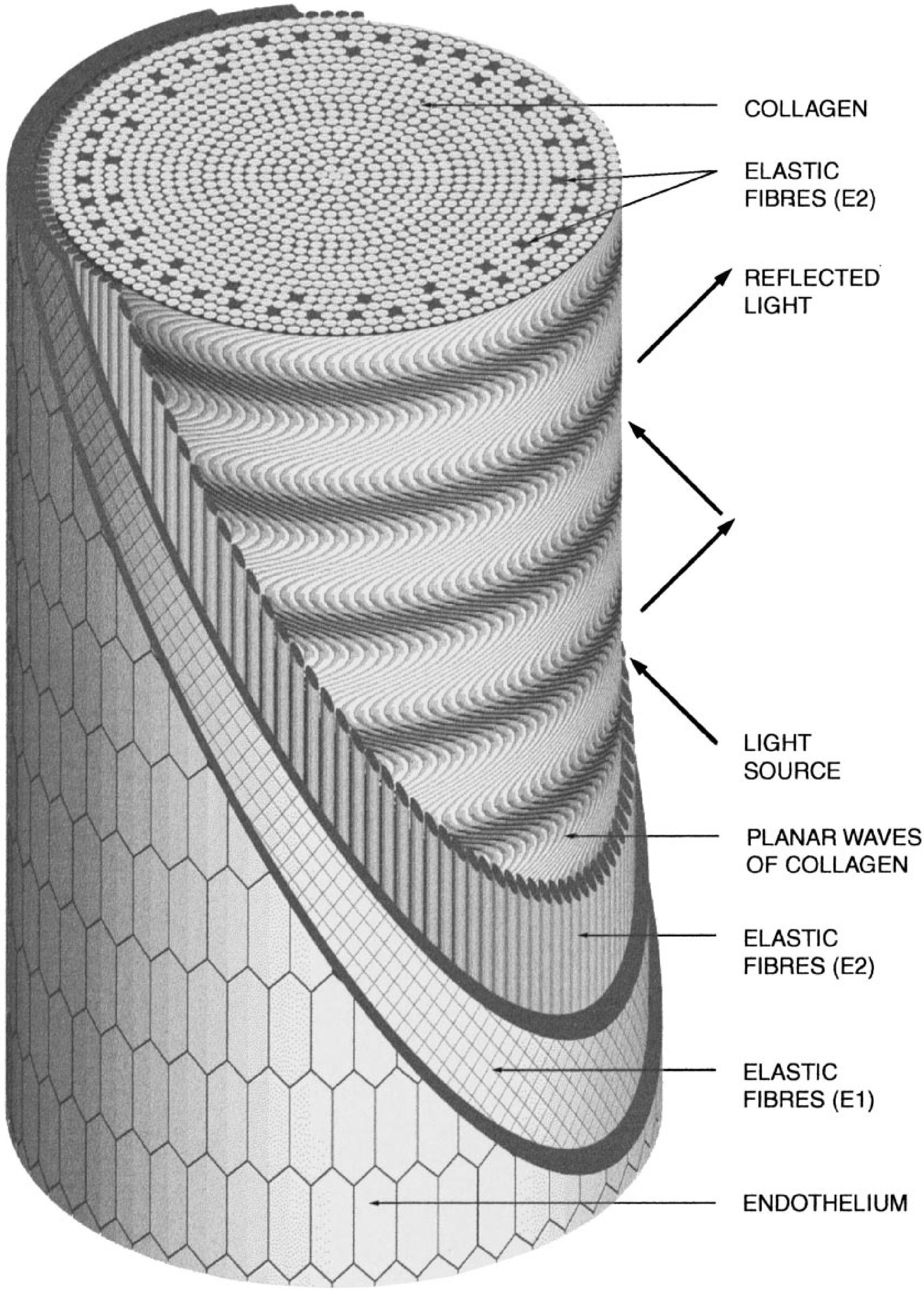


Fig. 5. Schematic diagram showing the main structural components of the chorda (not to scale).

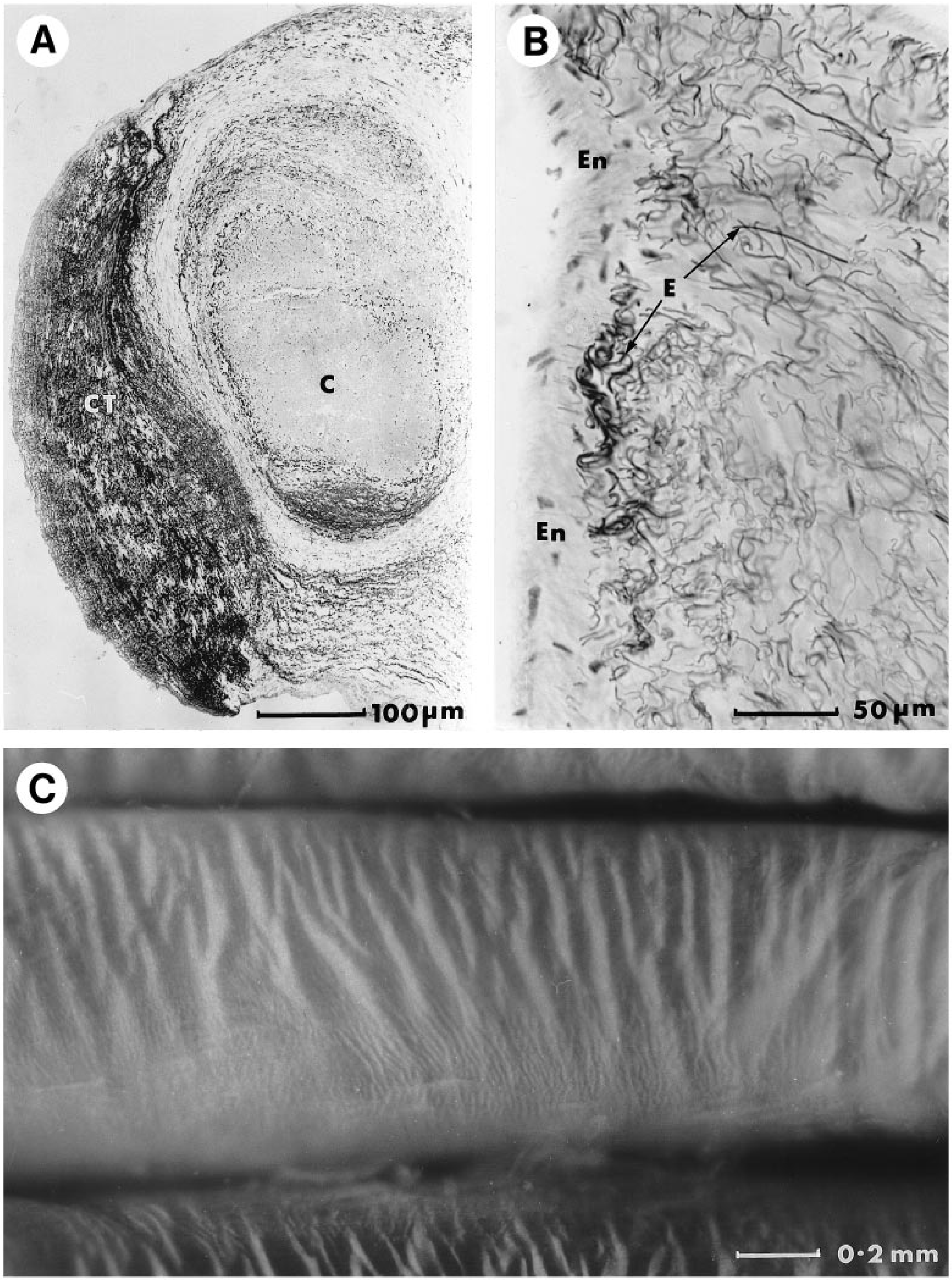


Fig. 6. (*A*) Cross-sectioned chorda originating from an elderly subject showing an extensive cushion of subendocardial connective tissues (CT). $\times 169$. C, collagen core of the chorda. (*B*) Enlarged fragment within the connective tissue cushion showing disorganised network of elastic fibres (E). $\times 322$. En, endothelium. (*C*) Reflected image from a chorda of an elderly subject showing a patch of 17 µm period regular stripes (compare with Fig. 2*A*) surrounded by disorganised region with a broad striped pattern. $\times 67$.

in relaxed chordae tendineae (Fig. 2*A*) correlate with the dimensions of undulations observed under the light microscope (Fig. 2*B*) and the scanning electron microscope (Fig. 4*C*). The regular wave pattern arranged in register was observed around the entire circumference of the relaxed chordae (Fig. 2*A*). This pattern extended towards the interior as shown on the scanning electron micrograph (Fig. 4*C*). On stretching the collagenous wavy pattern disappeared and was subsequently restored on reduction of tension. This observation indicates that collagen fibrils in their relaxed state are set in a regular wavy pattern which is permanent (Fig. 2*A*). Similar observations with unfixed specimens exclude the possibility that the wave pattern is a fixation artefact. In this context, the observations of Icardo & Colvee (1995) of undulating collagen in mouse chordae, show similarities to those presented in Figure 2*B*. Also, the observations of Lim & Boughner (1976) of disorganised wavy collagen obtained from the chordae of a young human individual show similarities to our observations. The presence in the chordae of young subjects of a regular 11 µm periodicity (Figs 2*A*, *B*) suggests that it is likely to be an early wave pattern which gradually changes and elongates with age, becoming eventually randomised showing an irregular broad striped pattern which resembled bands of Fontana (Stolinski, 1995*a*). The observations suggest that a process of gradual disorganisation of collagenous core related to ageing of the connective tissue was taking place.

The distribution of elastic tissue as observed by light microscopy in normal chordae follows a specific pattern. An approximately 4 µm thick layer consisting of a meshwork of elastic fibres was observed under the endothelium (Fig. 3) in addition to linearly disposed fibres dispersed deeper among collagen fibrils (Figs 2*B*, 3). These observations only partly agree with those of Fenoglio et al. (1972) who reported in the endocardium only occasional elastic fibres. Scanning electron microscopy confirmed close packing of linearly disposed elastic fibres situated underneath the endocardium (Fig. 4*B*). The presence of a sleeve-shaped elastic network which surrounds the internal collagen suggests that on relaxation of tension it would tend to restore the collagen fibrils within the chordae to their wavy configuration. It is perhaps significant that an analogous arrangement exists in peripheral nerve (Stolinski, 1995*a*) where elastic fibres were observed only in the external epineurial layers. In addition, the considerable thickness of the elastic tissue in the periphery of the chordae may act as a protective barrier between collagen and the delicate layer of the endocardium. All the described structures are presented diagramatically in Figure 5, showing the planar arrangement of the regular collagen waves and dual distribution of elastic fibres. The observed age changes of chordae structure are not only related to the loss of coherent wave structure (Fig. 6*C*). In addition, cushions of connective tissues (Fig. 6*A*) which appear in older subjects weaken the chordae while the size of the longitudinal core of dense collagen was found to be reduced. Also, unorganised and some circularly arranged fibres present in the cushions do not add to the overall strength of the chordae (Fig. 6*B*). The changes which were observed within the collagenous core of the chordae (Fig. 6*C*) illustrate the loss of coherency and disorganisation of the fibrils. It can be surmised that chordae stretching or eventual rupture may result from these 2 structural changes.

The specific configuration of fibres which make up the chordae must satisfy very demanding mechanical requirements in order to withstand the large repetitive forces encountered within the left ventricle of the heart. It is suggested that the wavy arrangement of collagen surrounded by elastic fibres is very well adapted for the cyclic stresses to which the chordae are continuously subjected. It also provides a mechanism for a smooth transfer of forces to the valve leaflets efficiently protecting the structural components of the valve which have to withstand rapidly applied forces at the systole. The undulating internal structure of the collagenous core reflects a very efficient design which has to maintain its integrity, strength and elasticity throughout the entire life of the organ. Further work will involve the measurement of changes in chordae parameters and establishing the ratio of type I–III collagens at a range of ages.

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